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A theoretical model for nucleate boiling of nanofluids considering the nanoparticle Brownian motion in liquid microlayer

Xiangdong Li [a], Yang Yuan [a], Jiyuan Tu [a,b,*]

[a] School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, PO Box 71, Bundoora, VIC 3083, Australia
[b] Key Laboratory of Ministry of Education for Advanced Reactor Engineering and Safety, Institute of Nuclear and New Energy Technology, Tsinghua University, PO Box 1021, Beijing 100086, China

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ABSTRACT

The forming of a porous layer of deposited nanoparticles on the heater surface is one of the unique phenomena in nucleate boiling of nanofluids. As the deposition of nanoparticles is induced by the evaporation of liquid microlayer, the average nanoparticle concentration in the microlayer is much higher than that in the bulk liquid. Therefore, the Brownian motion of nanoparticles in the microlayer may play an important role in dissipating heat from the heater surface. In this study, a new heat flux partitioning (HFP) model was proposed, in which a new heat flux component was incorporated to account for the heat transfer by nanoparticle Brownian motion in the liquid microlayer. The new heat flux component was formulated based on the latest experimental and theoretical research outcomes of microlayer evaporation. Comparison of the numerical results against the experimental data available in the literature proved that the new HFP model performs better than the classic HFP model. This study also demonstrated that the importance of nanoparticle Brownian motion is mainly controlled by the applied heat flux as it directly affects the number density of active sites on the heater surface. Finally, the effects of nanoparticle concentration, size and materials were also analyzed.

1. Introduction

Nanofluids are colloidal dispersions of nano-sized particles in common base liquids. Due to their enhanced properties associated with heat transfer and the promising prospects of industrial applications, nanofluids have been attracting an increasing number of investigations [1]. Following the study pioneered by Das et al. [2] in 2003, heat transfer by nucleate boiling of nanofluids has been intensively studied, mainly through experimental approaches. According to the literature surveys [3,4], two common findings have been thrown light on: (i) the significantly enhanced critical heat flux (CHF) and, (ii) the forming of a porous layer of deposited nanoparticles on the heater surface. These phenomena were observed in almost all the experiments, even in those using dilute nanofluids with extremely low nanoparticle concentrations [5]. For dilute nanofluids, numerous measurements [5,6] have proven that their properties including the saturation temperature, surface tension, thermal conductivity and viscosity are negligibly different from those of their pure base liquids. Thus, the dramatically enhanced CHF is attributed not to the negligibly changed liquid properties, but exclusively to the surface modifications induced by nanoparticle deposition [4].

In recent years, some efforts [7,8] have been devoted to develop predictive models for nucleate boiling of dilute nanofluids (typically with concentrations lower than 0.1 v%) based on the heat flux partitioning (HFP) model [9]. The effects of nanoparticles on the liquid properties were generally neglected in the models due to the aforementioned reasons, while focus was put mainly on the surface modifications and their effects on bubble dynamics [7,8]. Through incorporating the active site density correlation of Ganapathy and Sajith [10] and the bubble departure diameter correlation of Phan et al. [11], the improved HFP model [7,8] achieved a better agreement with the experimental data available in the literature than the classic HFP model by Kurul and Podowsk [9].

However, an important mechanism may have been ignored. As to the forming of porous layers, Kim et al. [5] and Kwark [6] proved that the deposition of nanoparticles is caused by the evaporation of liquid microlayer. As illustrated in Fig. 1, they proposed that when a bubble grows, the evaporating microlayer underneath the bubble leaves behind nanoparticles concentrating in it. The nanoparticles then adhere to the heater surface when the microlayer is

* Corresponding author at: School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, PO Box 71, Bundoora, VIC 3083, Australia. Tel.: +61 3 9925 6191; fax: +61 3 9925 6108.
E-mail address: jiyuan.tu@rmit.edu.au (J. Tu).

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Nomenclature

A_c	heater surface area fraction subjected to convection, (dimensionless)
A_q	heater surface area fraction subjected to quenching, (dimensionless)
c_{pl}	liquid specific heat, (J kg^{-1} K^{-1})
d_{bW}	bubble departure diameter, (m)
d_{np}	nanoparticle diameter, (m)
f	bubble departure frequency, (bubbles s^{-1})
h_c	convective heat transfer coefficient (W m^{-2} K^{-1})
h_{fg}	latent heat of evaporation, (J kg^{-1})
n	active site density, (sites m^{-2})
P	the system pressure, (Pa)
q	total wall heat flux, (W m^{-2})
q_{bm}	heat flux due to nanoparticle Brownian motion, (W m^{-2})
q_c	heat flux due to convection, (W m^{-2})
q_e	heat flux due to evaporation, (W m^{-2})
q_q	heat flux due to quenching, (W m^{-2})
R_a	average roughness of the clean heater surface, (m)
T_l	liquid temperature in the cell immediately next to the wall, (K)
T_{sat}	liquid saturation temperature, (K)
T_W	wall temperature, (K)
ΔT_{sub}	liquid subcooling, $T_{sat} - T_l$, (K)
ΔT_{sup}	wall superheat, $T_W - T_{sat}$, (K)
t_w	bubble waiting time, (s)

Greek symbols

φ	volumetric concentration of nanoparticles in nanofluid, (dimensionless)
λ	thermal conductivity, (W m^{-1} K^{-1})
μ	viscosity, (Pa s)
θ	contact angle, (radian)
ρ	density, (kg m^{-3})
σ	surface tension, (N m^{-1})

Subscripts

bm	Brownian motion
l	the liquid phase
lm	the liquid microlayer
np	the nanoparticles
v	the vapor phase

completely vaporized. This indicates that within the bubble growth time, the concentration of nanoparticles in the microlayer would keep increasing from the bulk value up to 100%. Therefore, the time-averaged nanoparticle concentration in the microlayer would be much higher than the bulk value. According to a literature survey by Wang and Mujumdar [12], the thermal conductivity enhancement of nanofluids at the atmospheric temperature could be as high as 60% when the nanoparticle concentration increased up to 5 v%. In addition, Das et al. [13] found that the effective thermal conductivity of nanofluids is a strongly increasing function of the temperature, much more considerable than that of pure liquids.

In fact, the enhanced thermal conductivity of nanofluids has been widely recognized and intensively studied. Since Jang and Choi [14] attributed the dramatically improved thermal conductivity of nanofluids, for the first time, to the Brownian motion of nanoparticles in the liquid, this viewpoint has been widely accepted and a number of theoretical models for predicting the effective thermal conductivity of nanofluids have been proposed [15–18]. According to these models, the heat transfer due to nanoparticle Brownian motion increases with the nanoparticle concentration. Therefore, as the microlayer is a layer of superheated liquid with elevated nanoparticle concentration, the heat transfer contribution by the Brownian motion of nanoparticles may be significant.

In this study, a new HFP model was proposed. Apart from the heat flux partitioning components for convection, evaporation and quenching, a new component accounting for the heat transfer by nanoparticle Brownian motion in the microlayer was also incorporated in the new model. In addition, in consideration of the surface modifications induced by nanoparticle deposition, new correlations for the nucleate boiling parameters were carefully developed and selected. Numerical computations were then conducted using the both HFP models and their numerical results were compared against the experimental data available in the literature. Further computations were also conducted to analyze the factors affecting heat transfer by the nanoparticle Brownian motion.

2. Heat flux partitioning in nucleate boiling of nanofluids

2.1. Heat flux partitioning in boiling nanofluids

For modeling of nucleate boiling of pure liquids, the classic HFP model developed by Kurul and Podowski [9] has been widely recognized as a mechanistic approach. According to this model, the total heat flux q applied at the heater surface could be partitioned into three components: the heat flux due to convection q_c, the heat flux due to evaporation q_e and that due to quenching q_q.

$$q = q_e + q_q + q_c \tag{1}$$

However, when nanoparticles exist in the liquid, the heat transfer mechanisms involved on the heater surface may be different. In this study, the HFP model was re-defined by adding a new component, q_{bm}, to model the heat transfer due to the nanoparticle Brownian motion. Therefore,

$$q = q_e + q_q + q_c + q_{bm} \tag{2}$$

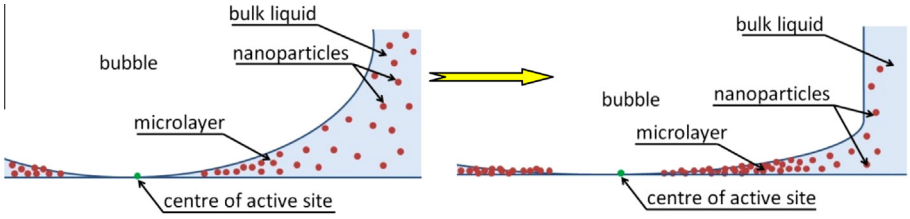

Fig. 1. Nanoparticle concentrating in microlayer as bubble grows.